Unintegrated parton distributions and pion production in pp collisions at RHIC's energies

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(Dated: February 9, 2008)

Abstract

We compare results of $2 \to 1$ k_t-factorization approach with Kwieciński unintegrated parton distributions and the standard collinear factorization approach at RHIC and slightly smaller energies. Our approach contains only one free parameter responsible for internal parton motion in nucleons. In contrast to recent works in the literature our k_t-factorization approach includes also quark degrees of freedom in addition to purely gluonic terms. Both mid and forward rapidity regions are considered. We discuss uncertainties due to fragmentation functions. In general, the k_t-factorization approach gives a better description of the $p_t \sim 1 - 4$ GeV region both at mid and forward rapidity regions. Our approach leads to asymmetry in the production of π^+ and π^-, very similar to the one observed very recently by the BRAHMS collaboration.

PACS numbers: 12.38.Bx, 13.85.Hd, 13.85.Ni

I. INTRODUCTION

In order to extend the applicability of the collinear-factorization approach (see e.g. [3, 4, 5, 7, 8]) to jet and/or meson production to small transverse momenta it was proposed to add an extra Gaussian distribution in the transverse momentum of colliding partons [6, 7, 8, 9, 10, 11, 12]. In addition to assuming the parameter of the Gaussian distribution to be x-independent, one has to substitute $t \to t - \mu^2$, $u \to u - \mu^2$ and $s \to s + 2\mu^2$ in order to avoid infinities in the matrix element squared contributing in this approach at finite transverse momenta. This procedure is an artifact of the on-shell approximation (on-shell, non-collinear partons) used. The result of such a procedure depends on the value of the parameter μ^2, especially at low transverse momenta. A part of the arbitrariness can be avoided in the k_t-factorization approach (see e.g. [13]).

The k_t-factorization approach was used recently to study both the rapidity and transverse momentum distributions of particles produced at RHIC energies [14, 15] with only gluon degrees of freedom taken into account. Recently we have supplemented the mechanisms including the gluon degrees of freedom with mechanisms including the quark degrees of freedom [13]. The latter are very important at very forward ($\eta \gg 0$) and very backward ($\eta \ll 0$) rapidity regions. Our approach makes use of the recently developed Kwieciński unintegrated parton distributions [16, 17, 18]. In contrast to other approaches in the literature the formalism takes into account the x-dependent radiative effect of k_t - broadening of "initial" parton distributions. The formalism of the Kwieciński UPDF is adequate in the region of not too small longitudinal momentum fractions i.e. at not too high energies. We have applied these unintegrated parton distributions to gauge boson [19], standard Higgs [20] hadroproduction as well as for charm-anticharm photoproduction [21]. Very recently we have applied this formalism also to the description of the SPS pion production data [13]. In the present analysis we shall apply it to the pion hadroproduction at somewhat larger energies, up to the RHIC energy W = 200 GeV.

II. INCLUSIVE CROSS SECTIONS FOR PARTONS

The approach proposed by Kwieciński is very convenient to introduce the nonperturbative effects like internal (nonperturbative) transverse momentum distributions of partons in

nucleons. It seems reasonable, at least in the first approximation, to include the nonperturbative effects in the factorizable way

$$\tilde{f}_i(x,b,\mu^2) = \tilde{f}_i^{pert}(x,b,\mu^2) \cdot F_i^{np}(b) \; , \tag{1}$$

where the index i denotes either gluons or quarks or antiquarks. The form factor responsible for the nonperturbative effects must be normalized such that [13]

$$F_i^{np}(b=0) = 1 \; . \tag{2}$$

In the following, for simplicity, we use a flavour and x-independent form factor

$$F_g^{np}(b) = F_q^{np}(b) = F_{\bar{q}}^{np}(b) = F^{np}(b) = \exp\left(-\frac{b^2}{4b_0^2}\right) \tag{3}$$

which describes the nonperturbative effects. The Gaussian form factor in b means also a Gaussian initial momentum distribution $\propto \exp(-k_t^2 b_0^2)$ (Fourier transform of a Gaussian function is a Gaussian function). Gaussian form factor is often used to correct collinear pQCD calculations for the so-called internal momenta. Other functional forms in b are also possible.

In the k_t-factorization approach usually the $gg \to g$ fusion mechanism is included only [14]. In Ref.[13] we have included two other leading-order diagrams which involve quark degrees of freedom. They are important in the so-called fragmentation region [13]. The momentum-space formulae for all the processes included read:

for diagram A (gg$\to$g):

$$\begin{aligned}
&\frac{d\sigma^A}{dy d^2p_t} = \frac{16 N_c}{N_c^2-1} \frac{1}{p_t^2} \\
&\int \alpha_s(\Omega^2) \; f_{g/1}(x_1,\kappa_1^2,\mu^2) \; f_{g/2}(x_2,\kappa_2^2,\mu^2) \\
&\delta^{(2)}(\vec{\kappa}_1 + \vec{\kappa}_2 - \vec{p}_t) \; d^2\kappa_1 d^2\kappa_2 \; ,
\end{aligned} \tag{4}$$

for diagram B$_1$ (q$_f$ g $\to$ q$_f$):

$$\begin{aligned}
&\frac{d\sigma^{B_1}}{dy d^2p_t} = \frac{16 N_c}{N_c^2-1} \left(\frac{4}{9}\right) \frac{1}{p_t^2} \\
&\sum_f \int \alpha_s(\Omega^2) \; f_{q_f/1}(x_1,\kappa_1^2,\mu^2) \; f_{g/2}(x_2,\kappa_2^2,\mu^2) \\
&\delta^{(2)}(\vec{\kappa}_1 + \vec{\kappa}_2 - \vec{p}_t) \; d^2\kappa_1 d^2\kappa_2 \; ,
\end{aligned} \tag{5}$$

for diagram B$_2$ (g q$_f$ $\to$ q$_f$):

$$\frac{d\sigma^{B_2}}{dyd^2p_t} = \frac{16N_c}{N_c^2-1}\left(\frac{4}{9}\right)\frac{1}{p_t^2}$$
$$\sum_f \int \alpha_s(\Omega^2)\ f_{g/1}(x_1,\kappa_1^2,\mu^2)\ f_{q_f/2}(x_2,\kappa_2^2,\mu^2)$$
$$\delta^{(2)}(\vec{\kappa}_1+\vec{\kappa}_2-\vec{p}_t)\ d^2\kappa_1 d^2\kappa_2\ . \tag{6}$$

These seemingly 4-dimensional integrals can be written as 2-dimensional integrals after a suitable change of variables [15]

$$\int\ ...\ \delta^{(2)}(\vec{\kappa}_1+\vec{\kappa}_2-\vec{p}_t)\ d^2\kappa_1 d^2\kappa_2 = \int\ ...\ \frac{d^2q_t}{4}\ . \tag{7}$$

The integrands of these "reduced" 2-dimensional integrals in $\vec{q_t} = \vec{\kappa_1} - \vec{\kappa_2}$ are generally smooth functions of q_t and corresponding azimuthal angle ϕ_{q_t}. In Eqs.(4), (5) and (6) the longitudinal momentum fractions

$$x_{1/2} = \frac{\sqrt{p_t^2+m_x^2}}{\sqrt{s}}\exp(\pm y)\ , \tag{8}$$

where m_x is the effective mass of the parton. This is important only at $p_t \to 0$ [13].

The sums in (5) and (6) run over both quarks and antiquarks. The argument of the running coupling constant Ω^2 above was not specified explicitly yet. In principle, it can be p_t^2 or a combination of p_t^2, κ_1^2 and κ_2^2. In the standard transverse momentum representation it is reasonable to assume $\Omega^2 = \min(p_t^2,\kappa_1^2,\kappa_2^2)$ (see e.g. [15]). In the region of very small p_t usually $p_t^2 < \kappa_1^2, \kappa_2^2$ and $\Omega_2 = p_t^2$ is a good approximation.

Assuming for simplicity that $\Omega^2 = \Omega^2(p_t^2)$ or p_t^2 (function of transverse momentum squared of the "produced" parton, or simply transverse momentum squared) and taking the following representation of the δ function

$$\delta^{(2)}(\vec{\kappa_1}+\vec{\kappa_2}-\vec{p_t}) = \frac{1}{(2\pi)^2}\int d^2b\ \exp\left[(\vec{\kappa_1}+\vec{\kappa_2}-\vec{p_t})\vec{b}\right]\ , \tag{9}$$

the formulae (4), (5) and (6) can be written in the equivalent way in terms of parton distributions in the space conjugated to the transverse momentum. The corresponding formulae read:

for diagram A:

$$\frac{d\sigma^{A}}{dyd^2p_t} = \frac{16N_c}{N_c^2-1}\frac{1}{p_t^2}\alpha_s(p_t^2)$$
$$\int \tilde{f}_{g/1}(x_1,b,\mu^2)\ \tilde{f}_{g/2}(x_2,b,\mu^2) J_0(p_t b)\ 2\pi b db\ , \tag{10}$$

for diagram B$_1$:

$$\frac{d\sigma^{B_1}}{dyd^2p_t} = \frac{16N_c}{N_c^2-1}\left(\frac{4}{9}\right)\frac{1}{p_t^2}\alpha_s(p_t^2)$$
$$\sum_f \int \tilde{f}_{q_f/1}(x_1,b,\mu^2)\ \tilde{f}_{g/2}(x_2,b,\mu^2) J_0(p_t b)\ 2\pi b db\ , \tag{11}$$

for diagram B$_2$:

$$\frac{d\sigma^{B_2}}{dyd^2p_t} = \frac{16N_c}{N_c^2-1}\left(\frac{4}{9}\right)\frac{1}{p_t^2}\alpha_s(p_t^2)$$
$$\sum_f \int \tilde{f}_{g/1}(x_1,b,\mu^2)\ \tilde{f}_{q_f/2}(x_2,b,\mu^2) J_0(p_t b)\ 2\pi b db\ . \tag{12}$$

These are 1-dimensional integrals. The technical price one has to pay is that now the integrands are strongly oscillating functions of the impact factor, especially for large p_t. The formulae (10), (11) and (12) are very convenient to directly use the solutions of the Kwieciński equations discussed in the previous section.

When extending running α_s to the region of small scales we use a parameter-free analytic model from ref.[22].

III. FROM PARTONS TO HADRONS

In Ref.[14] it was assumed, based on the concept of local parton-hadron duality, that the rapidity distribution of particles is identical to the rapidity distribution of gluons. In the present approach we follow a different approach which makes use of phenomenological fragmentation functions (FF's). In the following we assume $\theta_h = \theta_g$. This is equivalent to $\eta_h = \eta_g = y_g$, where η_h and η_g are hadron and gluon pseudorapitity, respectively. Then

$$y_g = \mathrm{arsinh}\left(\frac{m_{t,h}}{p_{t,h}}\sinh y_h\right)\ , \tag{13}$$

where the transverse mass $m_{t,h} = \sqrt{m_h^2 + p_{t,h}^2}$. In order to introduce phenomenological FF's one has to define a new kinematical variable. In accord with e^+e^- and ep collisions we define a quantity z by the equation $E_h = zE_g$. This leads to the relation

$$p_{t,g} = \frac{p_{t,h}}{z} J(m_{t,h}, y_h)\ , \tag{14}$$

where the jacobian $J(m_{t,h}, y_h)$ reads

$$J(m_{t,h}, y_h) = \left(1 - \frac{m_h^2}{m_{t,h}^2\cosh^2 y_h}\right)^{-1/2}\ . \tag{15}$$

Now we can write a given-type parton contribution to the single particle distribution in terms of a parton (gluon, quark, antiquark) distribution as follows

$$\frac{d\sigma^p(\eta_h,p_{t,h})}{d\eta_h d^2p_{t,h}} = \int dy_p d^2p_{t,p} \int dz \; D_{p\to h}(z,\mu_D^2)$$
$$\delta(y_p-\eta_h)\;\delta^2\left(\vec{p}_{t,h}-\frac{z\vec{p}_{t,p}}{J}\right)\cdot\frac{d\sigma(y_p,p_{t,p})}{dy_p d^2p_{t,p}}\;. \tag{16}$$

Please note that this is not an invariant cross section. The invariant cross section can be obtained via suitable variable transformation

$$\frac{d\sigma^p(y_h,p_{t,h})}{dy_h d^2p_{t,h}} = \left(\frac{\partial(y_h,p_{t,h})}{\partial(\eta_h,p_{t,h})}\right)^{-1}\;\frac{d\sigma^p(y_h,p_{t,h})}{d\eta_h d^2p_{t,h}}\;, \tag{17}$$

where

$$y_h = \frac{1}{2}\log\left[\frac{\sqrt{\frac{m_h^2+p_{t,h}^2}{p_{t,h}^2}+\sinh^2\eta_h}+\sinh\eta_h}{\sqrt{\frac{m_h^2+p_{t,h}^2}{p_{t,h}^2}+\sinh^2\eta_h}-\sinh\eta_h}\right]\;. \tag{18}$$

Making use of the δ function in (16) the inclusive distributions of hadrons (pions, kaons, etc.) are obtained through a convolution of inclusive distributions of partons and flavour-dependent fragmentation functions

$$\frac{d\sigma(\eta_h,p_{t,h})}{d\eta_h d^2p_{t,h}} = \int_{z_{min}}^{z_{max}} dz\frac{J^2}{z^2}$$
$$D_{g\to h}(z,\mu_D^2)\frac{d\sigma^A_{gg\to g}(y_g,p_{t,g})}{dy_g d^2p_{t,g}}\Bigg|_{\substack{y_g=\eta_h\\ p_{t,g}=Jp_{t,h}/z}}$$
$$+\sum_{f=-3}^{3} D_{q_f\to h}(z,\mu_D^2)\frac{d\sigma^{B_1}_{q_f g\to q_f}(y_{q_f},p_{t,q_f})}{dy_{q_f} d^2p_{t,q}}\Bigg|_{\substack{y_q=\eta_h\\ p_{t,q}=Jp_{t,h}/z}}$$
$$+\sum_{f=-3}^{3} D_{q_f\to h}(z,\mu_D^2)\frac{d\sigma^{B_2}_{g q_f\to q_f}(y_{q_f},p_{t,q_f})}{dy_{q_f} d^2p_{t,q}}\Bigg|_{\substack{y_q=\eta_h\\ p_{t,q}=Jp_{t,h}/z}}\;. \tag{19}$$

One dimensional distributions of hadrons can be obtained through the integration over the other variable. For example the pseudorapidity distribution is

$$\frac{d\sigma(\eta_h)}{d\eta_h} = \int d^2p_{t,h}\;\frac{d\sigma(\eta_h,p_{t,h})}{d\eta_h d^2p_{t,h}}\;. \tag{20}$$

There are a few sets of fragmentation functions available in the literature (see e.g. [23], [24], [26]).

IV. RESULTS

In the present application different fragmentation functions from the literature [23, 24, 26] will be used. All of them were obtained in global fits to the e^+e^- data. In the present paper we shall show related uncertainties for pion hadroproduction.

Before we go to the RHIC data we wish to look at some lower-energy data measured at ISR [27]. It was pointed out recently [5] that the standard collinear approach is not able to describe very forward production of π^0. In Fig.1 we present invariant cross section as a function of the Feynman x_F for W = 23.3 GeV at two different laboratory angles $\theta = 15^o$, 22^o. The collinear factorization result (left panel) lies well below the data independent of what fragmentation functions are used. The results of the k_t-factorization approach describe the experimental data much better. In Fig.2 we present similar results for somewhat larger

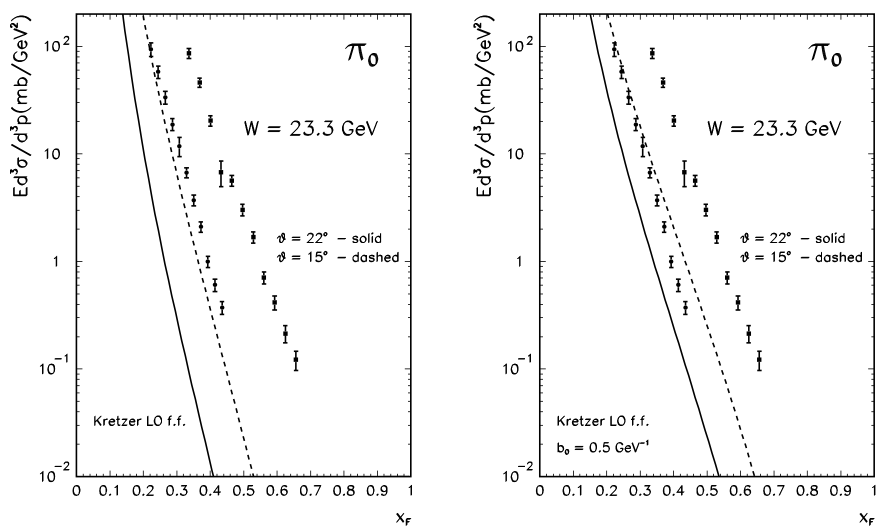

FIG. 1: Invariant cross section as a function of x_F at W = 23.3 GeV for different angles. The standard collinear result is shown in panel (a) and result of our approach in panel (b). The experimental data are from [27]

energy W = 52.8 GeV and $\theta = 5^o$, 10^o. The situation here is very similar to that at the lower energy.

Clearly, the standard collinear approach fails badly in the very forward region. The k_t-factorization is much better but still some contribution is missing at large Feynman x_F and at small transverse momenta. However, one should remember that other processes such as

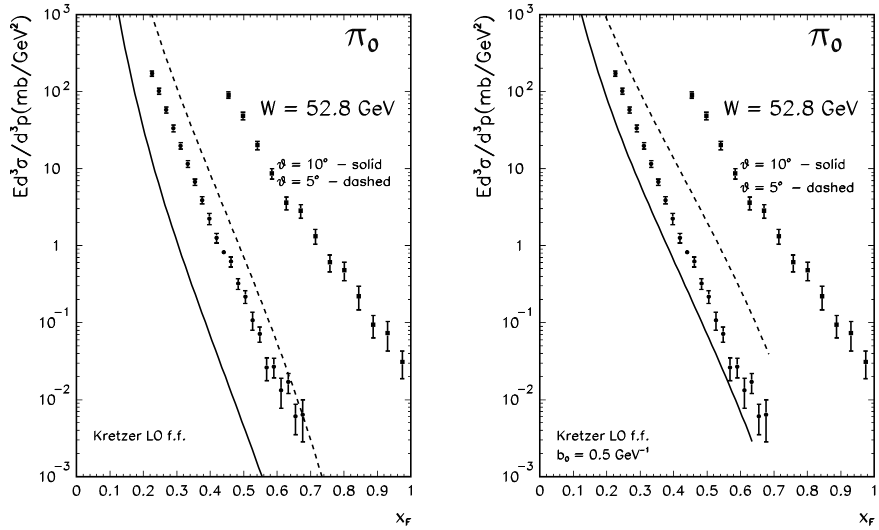

FIG. 2: Invariant cross section as a function of x_F at W = 52.8 GeV for different angles. The standard collinear result is shown in panel (a) and result of our approach in panel (b). The experimental data are from [27].

pion stripping [36] and/or diffractive production of nucleon resonances and their subsequent decay may play an important role here. This requires a separate analysis which goes beyond the scope of the present paper.

Let us return to the midrapidity region. The PHENIX collaboration has measured invariant cross section as a function of the π^0 transverse momentum at W = 200 GeV in a very narrow interval of pseudorapidity $\eta = 0.0 \pm 0.15$.

In Fig.4 we show our full result (diagrams A, B_1 and B_2 [13]) for different fragmentation functions [23, 24, 26]. In this calculation $b_0 = 0.5$ GeV^{-1} was used. This is the optimal value of the parameter for gauge boson production [19]. In Fig.3 we show the dependence on the value of the parameter b_0. Having in view the uncertainties in the fragmentation functions and in the parameter b_0, which is responsible for nonperturbative effects like e.g. parton Fermi motion, our k_t-factorization result describes the data very well and in a quite broad range of transverse momentum. In Fig.5 we show individual contributions of gluon and quark components. In contrast to the standard beliefs (see e.g. [14]) the quark contributions are only slightly smaller then the gluon ones and certainly not negligible, especially at larger transverse momenta.

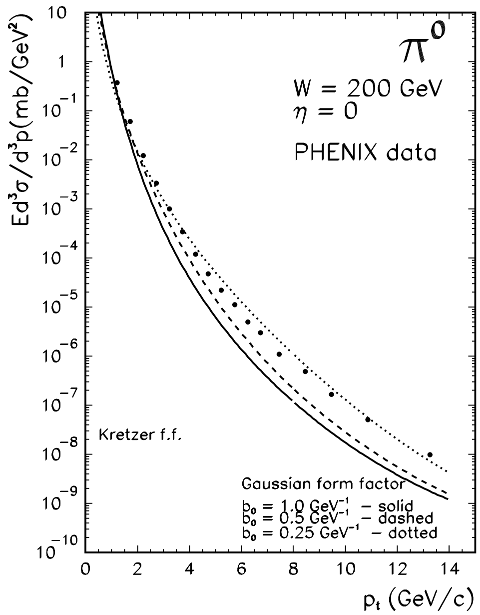

FIG. 3: Invariant cross section for π^0 production as a function of pion transverse momentum at W = 200 GeV and $\eta = 0.0$. The k_t-factorization results are shown for different values of the parameter b_0. The experimental data of the PHENIX collaboration are from [28].

Let us come now to charged particle distributions. In Fig.6 we show the results of the collinear approach for different values of hadron pseudorapidity for the Kretzer fragmentation functions [24]. The results of the calculations are compared to the BRAHMS collaboration data [29]. The theoretical calculations are for the charged pions. The data are not exactly for pions but include all charged hadrons, e.g. protons as well. There is a large factor of disagreement between the calculations and the data. This factor seems to increase when going from mid to forward rapidities which is not compatible with the NLO collinear factorization approach where the so-called K-factor is almost independent of rapidity. In Fig.7 we present result of our calculations for $b_0 = 0.5$ GeV and the Kretzer fragmentation functions [24]. While at large (pseudo)rapidities (η = 2.2, 3.2) our results (negative pions) are quite compatible with the experimental result for negative hadrons, there seems to be a missing contribution at more central (pseudo)rapidities (η = 0.0, 1.0), i.e. in the case when the sum of positively and negatively charged hadrons is measured. At present it is not clear to us if the missing strength is due to protons and/or positively charged kaons. In Fig.8 individual contributions from our k_t-factorization approach are shown. They correspond to diagrams

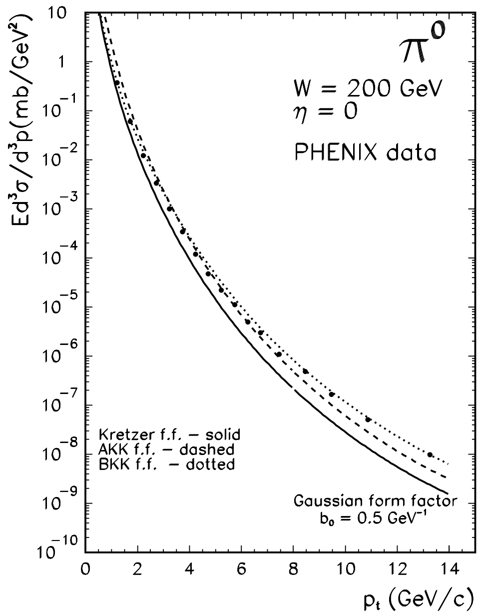

FIG. 4: Invariant cross section for π^0 production as a function of pion transverse momentum at W = 200 GeV and $\eta = 0.0$. The k_t-factorization results are shown for different sets of fragmentation functions. The experimental data of the PHENIX collaboration are from [28].

A, B_1 and B_2 in Fig.1 of Ref.[13]. While at $\eta = 0$ the $gg \to g$ contribution dominates up to $p_t \sim 3.5$ GeV at $\eta = 2.2$ the B_1 contribution is larger than the $gg \to g$ one already at $p_t \sim 1.5$ GeV and at $\eta = 3.2$ above $p_t \sim 1$ GeV. This is the B_1 contribution which provides a good description of the BRAHMS data at forward ($\eta \gg 2$) rapidities.

In Fig.9 we compare results of our calculations with the old proton-antiproton charged hadron data [31] for $\eta = 0$. The dependence on fragmentation functions is shown in the left panel. In the right panel we show the dependence on the parameter b_0 for the Kretzer fragmentation functions. The figure looks very similar to the figure with the BRAHMS collaboration data for $\eta = 0$, which simply reflects consistency of the proton-proton (BRAHMS) data and proton-antiproton (UA1) data. Within the approximations used in our approach the charged pion inclusive cross section is identical for the proton-proton and proton-antiproton collisions, provided the energy is the same, which is the case for the BRAHMS and UA1 colaboration data.

Let us concentrate now at the very forward region of the phase space. Recently the STAR collaboration has published [30] large-rapidity, intermediate-transverse-momentum data for

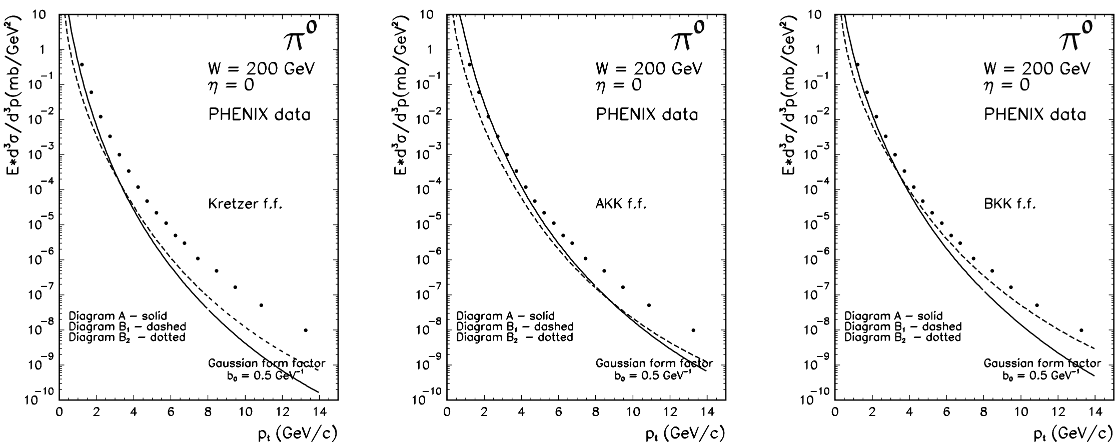

FIG. 5: Invariant cross section for π^0 production as a function of pion transverse momentum at W = 200 GeV and $\eta = 0.0$. Individual contributions of gluon and quark fragmentation are shown for different fragmentation functions. The experimental data of the PHENIX collaboration are from [28].

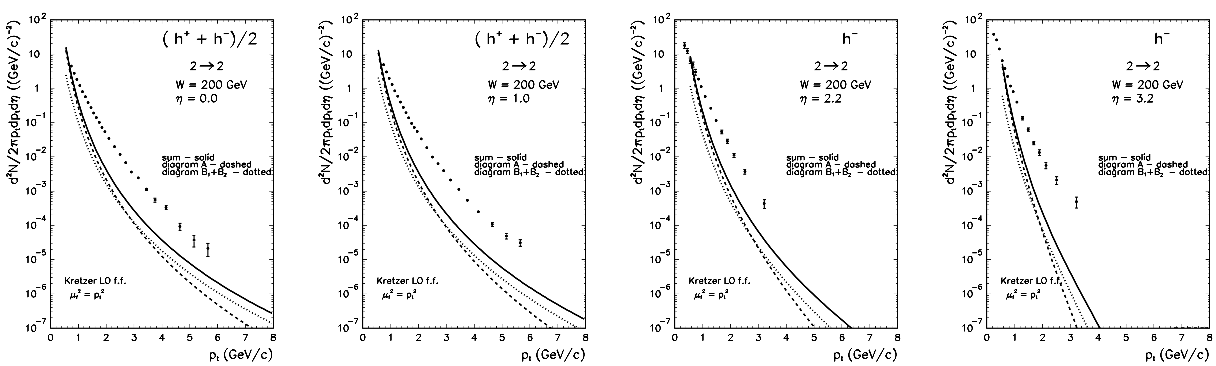

FIG. 6: Invariant cross section for charged particle production for different values of particle pseudorapidity at W = 200 GeV. The lines represent results obtained within standard collinear factorization approach and Kretzer fragmentation functions [24]. The BRAHMS collaboration experimental data [29] are shown by the solid circles.

π^0 production. In Fig.10 we compare the results of the collinear (left panel) and our k_t-factorization approach (right panel) calculated with the Kretzer fragmentation functions. While the collinear approach underestimates the STAR experimental data by a factor of about 3, the k_t-factorization approach is almost consistent with the data, especially at

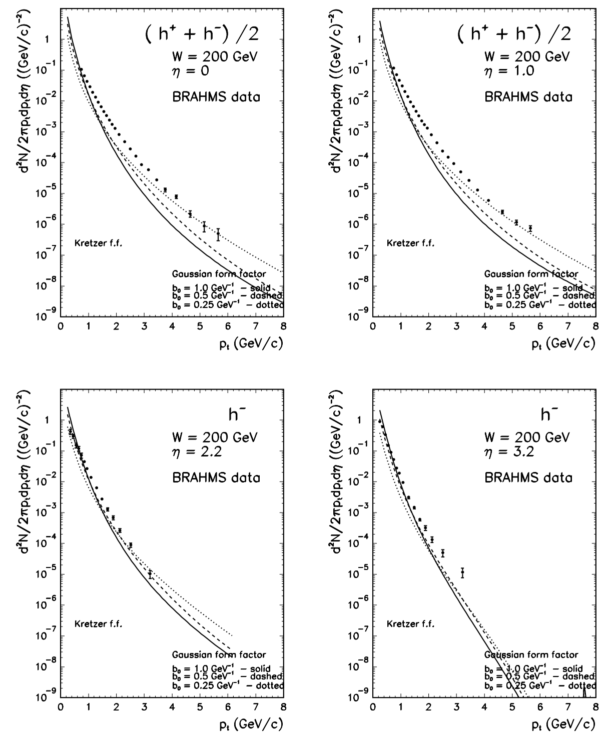

FIG. 7: Invariant cross section for charged particle production for different values of particle pseudorapidity at W = 200 GeV. The lines represent results obtained within our k_t-factorization approach for different values of parameter b_0 = 0.25, 0.5, 1.0 GeV^{-1} and Kretzer fragmentation functions [24]. The BRAHMS collaboration experimental data [29] are shown by the solid circles.

smaller pion energies, i.e. at not too high transverse momenta. The situation would change somewhat with different set of fragmentation functions.

In our approach the diagrams with quark degrees of freedom (B_1 and B_2) lead to an asymmetry in π^+ and π^- production. Recent results of the BRAHMS collaboration for the transverse momentum integrated cross section $d\sigma/dy$ show the $\pi^+ - \pi^-$ asymmetry already above y=2 [32]. As an example in Fig.11 we show the ratio of the corresponding cross sections for π^- and π^+ production for the STAR kinematics. A huge deviation from the unity can be observed. The k_t-factorization approach ratio (thick solid line) is somewhat smaller than the corresponding ratio in the collinear approach (dashed line).

During the preparation of this manuscript the BRAHMS collaboration has presented the first preliminary data for identified π^+ and π^- [33]. In Fig.12 we show transverse momentum dependence of the ratio π^-/π^+ for rapidity y = 3.1. Only statistical error bars

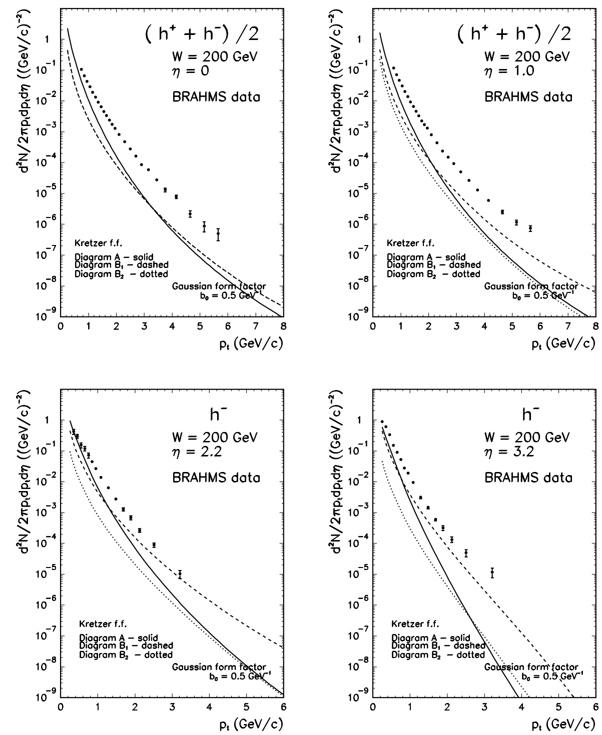

FIG. 8: Invariant cross section for charged particle production for different values of particle pseudorapidity at W = 200 GeV. The lines show individual contributions within our k_t-factorization approach. Here Kretzer fragmentation functions [24] were used. The BRAHMS collaboration experimental data [29] are shown by the solid circles.

are shown. Although the experimental ratio is not completely monotonous it clearly shows a deviation from unity which is an experimental evidence that gluon degrees of freedom are not sufficient to describe the production of hadrons. We describe the main trend of deviation of the ratio from unity relatively well except in the region of very small values of transverse momenta. [37] Of course such a ratio depends on the details of the fragmentation functions and in particular on their flavour decomposition which as discussed above is very difficult to obtain from the e^+e^- scattering alone. We hope that in the near future the BRAHMS collaboration will be able to scan the π^-/π^+ ratio as a function of (pseudo)rapidity and transverse momentum in order to identify the contributions with quark degrees of freedom and perhaps to extract flavour-dependent fragmentation functions.

In nuclear collisions the $\pi^+ - \pi^-$ asymmetry is weakened by the presence of the pp, nn, pn and np subcollisions. Due to isospin symmetry relation, this leads to equal yield of π^+

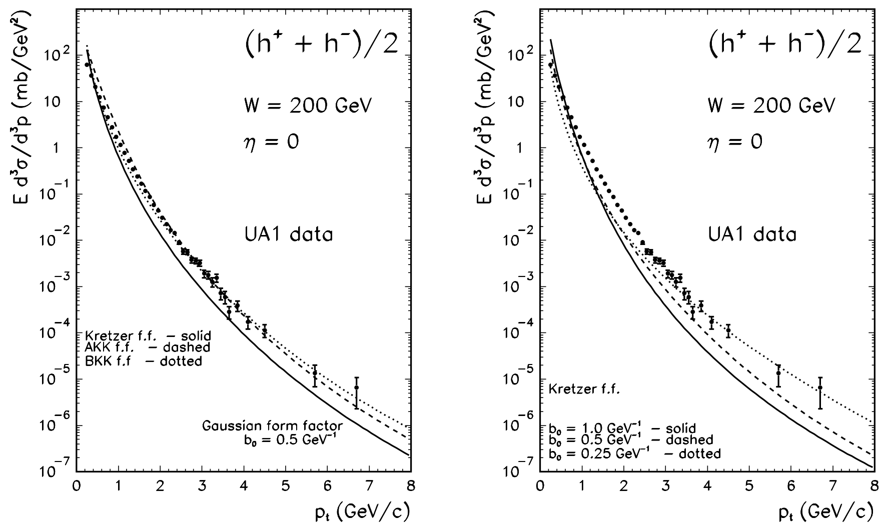

FIG. 9: Invariant cross section for charged particle production for different values of particle pseudorapidity at W = 200 GeV. The uncertainties on fragmentation function are discussed in the left panel and the dependence on the b_0 parameter in right panel. The UA1 collaboration experimental data [31] are shown by the solid circles.

and π^- for collisions of isospin symmetric nuclei. For collisions of heavy nuclei there is a small nonzero effect due to the excess of neutrons over protons. The asymmetry can be, however, quite sizeable in peripheral collisions [34] due to neutron skin effects. The sign of the nuclear asymmetry is then reversed as compared to the proton-proton collisions. The small asymmetry in nuclear collisions was recently mistakenly interpreted as a dominance of purely gluonic effects even at large rapidities. Our calculation actually shows that the quark terms dominate at very forward/backward rapidity regions. Although our calculation is for elementary proton-proton collisions only it puts into question some recent nuclear color glass condensate calculations based on gluon degrees of freedom only.

V. CONCLUSIONS

We have shown that the formalism recently developed by us and based on unintegrated parton distributions which fulfill the so-called Kwieciński evolution equations provides a reasonable description of the recent experimental data of the PHENIX, BRAHMS and STAR

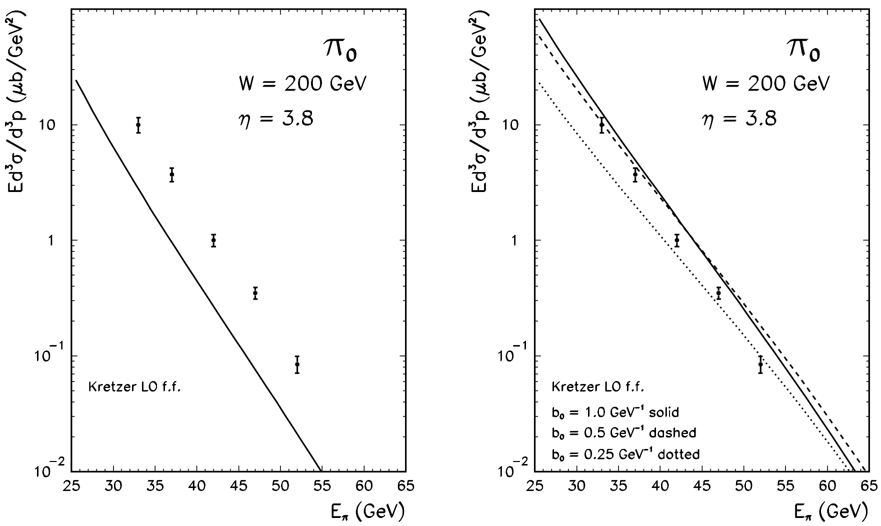

FIG. 10: Invariant cross section for neutral pion production as a function of pion energy at W = 200 GeV for $\eta = 3.8$ for collinear (left panel) and our k_t-factorization (right panel) approach. The STAR collaboration data are taken from Ref.[30].

collaborations at RHIC. The description is particularly good in the region of intermediate transverse momenta of pions $p_{t,h} \sim 1 - 4$ GeV. In comparison, the standard collinear factorization approach gives results which are by a factor of 3 – 7 lower than the experimental data, depending on particle rapidity. We have found a rather strong dependence on the set of fragmentation functions used in the calculation.

Inclusion of diagrams with quark degrees of freedom leads to $\pi^+ - \pi^-$ asymmetry. The preliminary BRAHMS data provide evidence for such an asymmetry. A dedicated measurement of the $\pi^+ - \pi^-$ asymmetry in forward and backward region as a function of transverse momentum would be a good test of the present approach and perhaps could be used to constrain better the gluon-to-pion and quark-to-pion fragmentation functions which extraction in e^+e^- collisions is ambigous to a large extent.

Acknowledgements We are indebted to Radosław Karabowicz for providing us with preliminary results of the BRAHMS collaboration for π^+ and π^- production presented at Quark Matter 2005. We are also indebted to Peter Levai for an interesting discussion about collinear approach and Stefan Kretzer for a discussion about parton fragmentation functions.

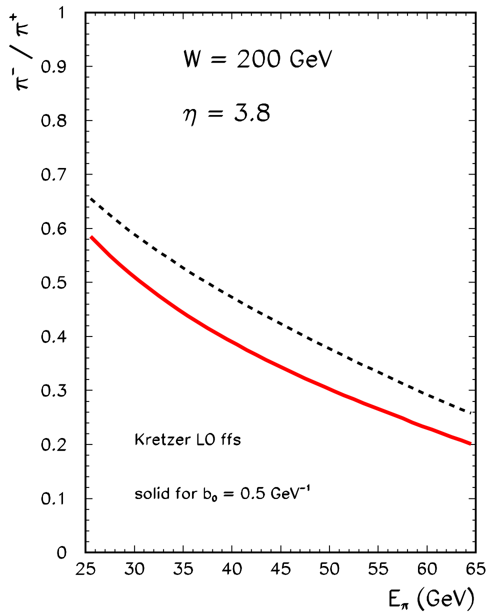

FIG. 11: The ratio of the π^- to π^+ cross sections as a function of pion energy for $\eta = 3.8$ for collinear (dashed) and our k_t-factorization (thick solid) approach.

This work was partially supported by the Polish KBN grant no. 1 P03B 028 28.

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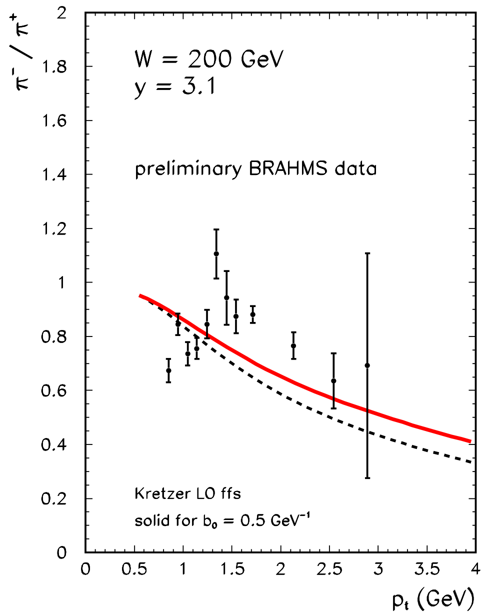

FIG. 12: The ratio of the π^- to π^+ cross sections as a function of pion transverse momentum for y = 3.1 for collinear (dashed) and our k_t-factorization (thick solid) approach. The data are from a recent presentation at Quark Matter 2005 conference [33].

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